

X-RAY BINARY POPULATIONS: THE LUMINOSITY FUNCTION OF NGC1569

K. BELCZYNSKI^{1,2}, V. KALOGERA¹, A. ZEZAS³, AND G. FABBIANO³

¹ Northwestern University, Physics & Astronomy, 2145 Sheridan Rd., Evanston, IL 60208

² Lindheimer Postdoctoral Fellow

³ Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138

belczynski, vicky@northwestern.edu; azezas, pepi@head.cfa.harvard.edu

Accepted to *The Astrophysical Journal, Letters* (December 16, 2003)

ABSTRACT

Using the population synthesis code *StarTrack* we construct the first synthetic X-ray binary populations for direct comparison with the X-ray luminosity function (XLF) of NGC 1569 observed with *Chandra*. Our main goal is to examine whether it is possible to reproduce the XLF shape with our models, given the current knowledge for the star-formation history of this starburst galaxy. We thus produce hybrid models meant to represent the two stellar populations: one old, metal-poor with continuous star-formation for ~ 1.5 Gyr and another recent and metal-rich population. To examine the validity of the models we compare XLFs calculated for varying ages of the populations and varying relative weights for the star-formation rates in the two populations. We find that, for typical binary evolution parameters, it is indeed possible to quite closely match the observed XLF shape. The robust match is achieved for an age of the young population and a ratio of star formation rates in the two populations that are within factors of 1.5 and 2, respectively, of those inferred from HST observations of NGC 1569. In view of this encouraging first step, we discuss the implications of our X-ray binary models and their potential as tools to study binary populations in galaxies.

Subject headings: binaries: close – stars: evolution – galaxies: individual (NGC 1569) – X-rays: binaries

1. INTRODUCTION

X-ray binaries (XRB) in nearby galaxies have been known since the *Einstein* era, but detections of significant samples were limited to just a few sources (e.g., Magellanic Clouds or M31) and interpretation of the source properties was often hampered by confusion problems. *Chandra* observations have revolutionized XRB studies with the discovery of large numbers of point X-ray sources in galaxies even beyond the Local Group (e.g., Fabbiano & White 2003). Short-term variability of many sources excludes the possibility of source confusion and strongly points toward accretion as the origin of the X-rays. The samples in most cases are large enough that we are now able to examine XRB *populations* in a wide range of galactic environments with different star formation histories. The samples are characterized by cumulative X-ray luminosity functions (XLFs) fitted by single or broken power-laws (e.g., Grimm et al. 2003; Zezas & Fabbiano 2002).

It has been noted that the XLF slopes follow a rather systematic behavior with population age and possibly star formation rate (SFR) (Grimm et al. 2003; Sarazin et al. 2003). Such behavior could constrain the SF history and properties of XRB populations in nearby galaxies. However, the development of reliable diagnostics requires a sound physical understanding of the observed correlations. With the exception of a recent study (Sipior et al. 2003, which does not focus on a specific set of observations), attempts to gain physical insight have been based so far on analytical models that *assume* the existence of power-law XLFs, and that X-ray lifetime is inversely proportional to X-ray luminosity and XRB properties do not depend on the SF history of the host galaxy (Wu 2001; Kilgard et al. 2002).

In order to develop a set of useful diagnostics, it is important to develop theoretical models for XRB formation and evolution that depend on the star-formation history of the host galaxies, and allow us to identify the main physical elements that determine the XLF slopes. Given that this study focuses on observed *populations*, it is clear that the employment of population synthesis models is necessary. First pre-Chandra XRB models for starbursts were developed and compared to ASCA observations of the total X-ray luminosity of WR galaxy He2-10 by Van Bever & Vanbeveren 2000. However, only now we may compare the specific theoretical models with the observed point source populations. A collaborative effort has led to the development of a detailed population synthesis code *StarTrack* (see § 2) that specifically focus on careful, self-consistent XRB calculations. Ultimately our goal is to construct a coherent picture of XRB formation and evolution based on theoretical models that have been first calibrated against observations of well-studied galaxies, and thus can be used in the interpretation of other XLF observations.

In this *Letter* we compare our model XLFs to *Chandra* observations of NGC 1569, a blue dwarf Irregular at a distance of 2.2Mpc (Israel 1988), characterized as a (post-)starburst galaxy. It has been selected as a good test case because its star formation history is *relatively* well constrained by HST optical and infrared observations (Aloisi et al. 2001; Greggio et al. 1998; Vallenari & Bomans 1996) and has a long (~ 80 ks) *Chandra* exposure providing a detection limit of $\simeq 10^{36}$ erg s $^{-1}$ (Martin, Kobulnicky & Heckman 2002; hereafter M02). We are mainly concerned with two questions: (i) is it at all possible to theoretically reproduce the observed XLF? and (ii) do our models agree with the current constraints on the star-formation history of NGC 1569 derived by

observations in other wavelenghts?

2. THEORETICAL MODELS

The *StarTrack* code was originally developed for the modeling of binaries with two compacts (BKB), but has recently undergone major revisions (Belczynski et al. 2003, in preparation) intended to treat in detail the formation and evolution of XRBs, for any choice of SF history and metallicity. The main revisions include a detailed treatment of tidal synchronization and circularization (Hut 1981), individual treatment of various mass-transfer (MT) episodes, full numerical orbit evolution with angular momentum losses due to magnetic breaking, gravitational radiation, mass transfer/loss, and tides.

We have calibrated the tidal implementation using observations of binary eccentricities and periods in stellar clusters (Mathieu et al. 1992) and of orbital decay in high-mass XRBs (Levine et al. 2000). Our MT implementation involves the detailed calculation of Roche-lobe overflow MT rates based on radius-mass exponents both for the donor stars and their Roche lobes. We have compared our results for a set of MT sequences to both published MT calculations (e.g., Beer & Podsiadlowski 2002) and results obtained within our group using an updated stellar evolution code (Ivanova et al. 2003) with very satisfactory agreement, much better than typical MT implementations. The modeled X-ray phases are identified as (i) stable, driven by nuclear evolution of the donor, magnetic braking or gravitational radiation (ii) thermally unstable with possibly anisotropic emission (King et al. 2001); (iii) Eddington-limited MT (cf. Kalogera et al. 2003, in preparation); and (iv) persistent or transient (critical MT rate from Dubus et al. 1999). We also account for wind accretion onto compact objects following Hurley, Tout & Pols (2002). The updated code has been already tested and used for a study of Galactic ultracompact binaries (Belczynski & Taam 2003).

In this paper we examine whether XRB models with rather standard binary-evolution parameters (i.e., not specifically selected for this study), but with star-formation history and metallicity consistent with what is known about NGC 1569 can produce an XLF shape in agreement with observations. We choose parameters from the reference model in BKB, with just a few differences: the maximum neutron star (NS) mass is set equal to $2 M_{\odot}$, the most recently inferred natal NS kick distribution is incorporated (Arzoumanian, Chernoff & Cordes 2002), the primary masses are selected in the range $4 - 100 M_{\odot}$ (with an initial-mass-function slope of -2.7; see Kroupa, Tout & Gilmore 1993), and the secondary masses in the range $0.08 - 100 M_{\odot}$ with a flat mass ratio (secondary divided by primary mass) distribution.

We construct our XRB models with focus on the estimated metallicities and SFR properties of stellar populations in NGC 1569. A coherent picture has been developed (Aloisi et al. 2001; Greggio et al. 1998; Valenari & Bomans 1996) for two populations: (i) one metal-rich ($\sim 0.25 Z_{\odot}$, although it could be comparable to $1 Z_{\odot}$; M02), young population formed in a global burst of star formation that lasted about 100 Myr and seems to have stopped 5-10Myr ago, and (ii) one metal-poor ($Z = 0.004 - 0.0004$), old population formed by less vigorous (possibly by a factor of 10 – 20 in SFR),

continuous star formation for the past 1-1.5 Gyr. For consistency with these estimates we adopt $Z = 0.005$ and $Z = 0.0022$, for the young and the old populations, respectively. We examine the consistency of our models by allowing the relative SFR weight and the population age and metallicity to vary.

3. THE X-RAY LUMINOSITY FUNCTION

We analyzed the archival *Chandra* data using the Ciao v3.0 data analysis suite. After screening for high background intervals we searched for sources in the full 0.3–7.0 keV band with the *wavedetect* source detection algorithm. Then, for each source within the D25 ellipse of the galaxy ($D_{\max} = 3.6'$, $D_{\min} = 1.8'$), we estimated the net number of counts using an aperture including all the emission from a source. The background was determined locally from a source-free annulus around each source. We detected 14 sources with a significance greater than 3σ above the local background, in excellent agreement with M02, but we exclude one that has been identified as a supernova remnant by M02. Based on the *LogN-LogS* relation from the *Champ* survey (Kim et al. 2003) we estimate that at most two of our sources within the D25 area are associated with background or foreground objects.

The relatively high number of counts of the faintest sources ($\sim 15 - 20$ counts) compared to their typical background ($\sim 5 - 10$ counts) and the lack of a turnover in the observed cumulative XLF (see Figure 2) indicate that incompleteness is not significant in the low luminosity end of the XLF. The higher level of diffuse emission in the central region of the galaxy (M02) may result to a higher detection threshold, but, given the very small number of sources in this region, we do not attempt to correct for this effect. In our XLF, apart from the standard Gehrels errors (Gehrels 1986), we include errors associated with the uncertainties in the observed count rate of each source, following Zezas & Fabbiano (2002). The luminosity of the sources is in the 0.1-10.0 keV band assuming a power-law spectrum ($\Gamma = 1.7$) with Galactic column density ($2.3 \times 10^{20} \text{ cm}^{-3}$) and is corrected for absorption.

In our theoretical models X-ray luminosities (L_X) are calculated based on the *accretion* rate \dot{M} with appropriate efficiencies for NS and black holes (BH). At present no corrections specific to the *Chandra* energy band are taken into account, due to the lack of a reliable spectral model across a wide range of frequencies. We further apply the Eddington limit and calculate the effects of associated non-conservative mass transfer with the lost matter carrying away the specific angular momentum of the accretor.

To determine the contribution of transient systems to the XLF we need information on their X-ray duty cycle (DC), which however cannot be provided reliably by the disk instability theory. Empirically it is thought that $DC \lesssim 1\%$ (e.g., Taam, King & Ritter 2000). In *StarTrack* we adopt a DC value (in this study DC=1%) and, for each system we randomly sample the probability that the source is in outburst and then assign an X-ray luminosity equal to the Eddington limit, whereas for the systems in quiescence we assume that their X-ray luminosities are too low to be detectable. Donors more massive than the accretors can drive mass transfer on their thermal timescale (e.g., Kalogera & Web-

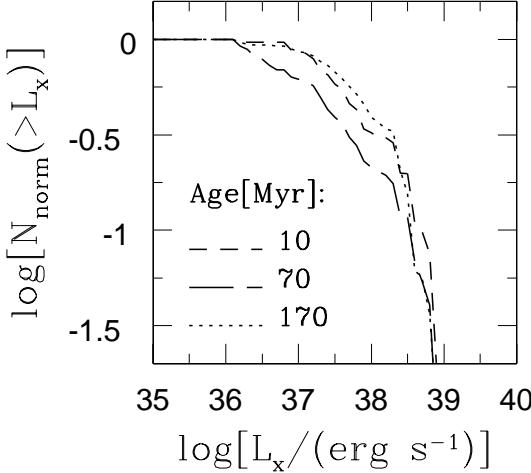


FIG. 1.— Non-monotonic behavior with time of theoretical normalized XLFs for two stellar populations: one old at 1.5 Gyr and one young at age 10, 70, and 170 Myrs (continuous SFR through 1.5 Gyr, and 10, 70, and 100 Myrs, respectively). the average SFR in the old population is assumed to be 20 times smaller than that in the young population.

bink1996) and anisotropic emission is possible (King et al. 2001). We identify such systems based on the calculated radius-mass exponents. At present we do not account for the anisotropic-emission possibility, but do account for the possibility of super-Eddington transfer as described above. Both transient and thermal-timescale XRBs are Roche-lobe overflow (RLOF) systems, and typically dominate old ($\gtrsim 100$ Myr) populations (see also Sipior et al. 2003).

Based on the current understanding of the SF history of NGC1569 (§ 2), we calculate combined XLFs for ages 1–1.5 Gyr and 70–110 Myr, for the old and young populations, respectively. The choice of the relative weight of the two populations also affects the XLF shape and we choose SFR weight factors in the range 10–50. Population models tend to have rather uncertain absolute normalizations and the absolute SFRs in NGC 1569 are not well constrained either (Vallenari & Bomans1996). Although, the total number of sources in a galaxy (corrected carefully for selection effects, partial galaxy coverage, etc) can provide additional model constraints, in this first step of our studies we restrict ourselves to calibrations and comparisons to observations based on the XLF *shape*. Therefore we used observed and model XLFs normalized to the total number of objects, and we take into account the small-number bias by randomly selecting from the simulated source populations samples of 13 sources at a time. The sampling of the underlying model parent population is then repeated number of times ($\sim 10^4$) to yield the predicted XLFs and their associated errors.

Figure 1 indicates the behavior of XLF as a function of age of young XRB population of NGC1569, while the age of the old population is fixed at 1.5 Gyr. Unlike earlier suggestions (Wu 2001; Kilgard et al. 2002), we find that the dependence of the XLF slope on age is *non-monotonic* and this can be actually understood physically. At early times (~ 10 Myr) the XLFs are by far dominated by MT-fed systems of the older population. The recent star formation episode barely begun producing wind-fed systems with the most massive compact

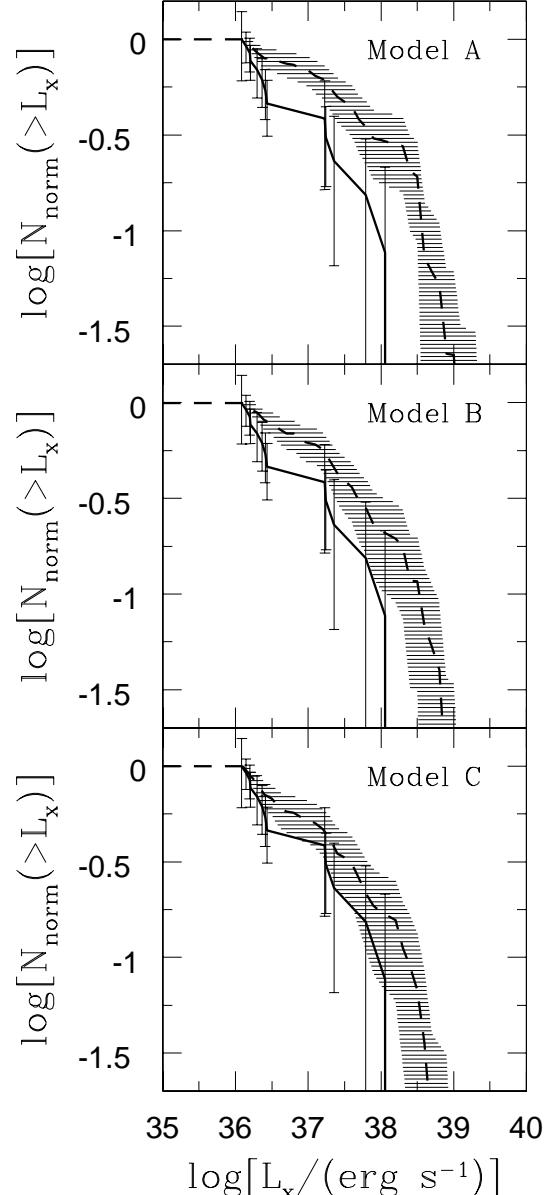


FIG. 2.— The observed NGC1569 XLF with error bars (solid lines) plotted against predicted XLFs (dashed curves) shown with 1σ sampling errors (shaded areas). All curves are normalized to the total number (13) of the detected sources. Each panel corresponds to different choices for the age of the young and old populations and the SFR ratio of the young relative to the old, respectively. *Top panel:* 110 Myr, 1.5 Gyr, and 20; *Middle panel:* 70 Myr, 1.5 Gyr, and 20; *Bottom panel:* 70 Myr, 1.3 Gyr, and 40.

objects (formed earlier) that accrete from strong winds from the next most massive donors. The combination of young and bright wind-fed sources with the MT-fed systems of older population tends to make XLFs rather flat. However, relatively quickly (~ 70 Myr) the very massive stars of young population end their lives and are removed from the XRB sample. They are replaced by less massive, and fainter wind-fed systems and the XLF becomes steeper. As time passes (~ 170 Myr) RLOF systems of younger population, that tend to be brighter than wind-fed sources of similar binary component masses, start becoming important in the total population and the XLF slope once again becomes flatter.

In Figure 2 we present XLFs calculated for NGC1569.

TABLE 1. MODEL C XRB SUB-POPULATIONS^a

Type	Old Pop.	Young Pop.
RLOF systems	24.4%	3.7%
NS/BH accretor	1.5	4.0
transient ^b /persistent	0.1	no trans.
thermal/rest	0.38	0.25
WIND-fed systems	1.5%	70.4%
NS/BH accretor	1.0	0.53

^aCorresponds to all active ($L_x > 1.22 \times 10^{36} \text{ erg s}^{-1}$) sources.

^bOnly transients at outburst stage are listed here assuming DC=1%.

Model A with parameters taken at face value from the HST observations: young population at 110 Myrs with SFR of 20 times larger than that of the old population at 1.5 Gyr. The calculated function tends to be flatter and extends to higher L_X values compared to the observed XLF. At the age of 110 Myr since the onset of the burst (10 Myr after its end), the young population includes a significant number of a bright RLOF sources flattening the XLF. Model B corresponds to the young population at an earlier age of 70 Myrs (equal to the burst duration) when it is dominated by high mass XRBs, and we already see that the XLF becomes steeper, but not quite enough to match the observed one. There are still quite a few RLOF systems formed in the old star formation episode. However, the duration of that episode as well as its end time are not very precisely established. Model C corresponds to the young population at 70 Myrs (equal to the burst duration), but the old one at 1.3 Gyr with continuous star formation for 1 Gyr. The predicted XLF quite closely match the observed one within the relevant errors. We note the tendency for higher luminosities in the models, but we note that we adopt bolometric luminosities, which are higher than those in the *Chandra* band. In Table 1 we present the content of the X-ray binary population for our best model (C). The population is dominated by young high-mass XRBs, but with significant contribution of old RLOF systems. In the young population, where only the most massive stars have ended evolution, many accretors are BH, while in the older population sources with NS dominate.

4. DISCUSSION

We present our first results from XRB population models developed for comparison with current and future *Chandra* observations of nearby galaxies. We choose NGC 1569 as our first test case and we find good agreement between our models and the observations. This agreement is even more remarkable in view of the fact

that we did not attempt to fine tune any of the model parameters related to X-ray binary evolution. However, we have explored other models with varying metallicities and IMF slopes, and found that both our quantitative and qualitative conclusions remain robust and the other models do not offer a better match to the observed XLF shape. This is true even when we account for the fraction of systems that can escape NGC 1569, due to systemic velocities acquired at supernova explosions.

Examination of various models with properties consistent with NGC 1569 constraints, lead us to conclusion that an age of 70 Myr for the young and 1.3 Gyr for the old population and a SFR relative weight of 40 are favored. In order to get agreement between the model and the observed XLF, we require a recent burst that is younger than inferred from the optical/infrared data. This slight discrepancy could be due to the fact that at this point we do not consider different black-hole binary spectral states and anisotropic emission from pulsar binaries. On the other hand the parameters of the older population (which is dominated by old non-magnetized neutron star binaries) are very consistent with the latest picture from the HST data (Angeretti et al. 2003, private communication).

We consider these encouraging results only a small, first step in our exploration of XRB models and their comparison to observations. As we gain experience with the study of specific galaxies, we expect to develop a reliable calibration system that will then allow us to extract information about origin of XRBs in other galaxies. A natural extension of this study will include two elements: the exploration of constraints on the absolute normalization of the XLF in addition to its shape, and the comparison models with a sample of starburst galaxies that form a time sequence with ages in a wide range of values to address the theoretical basis for correlations suggested by Grimm et al. (2003), for example. Detailed examination of degeneracies in the derived constraints is also important. Moreover, the modeling of supernovae remnants may prove to be necessary, since they may *i*) contribute significantly to and *ii*) be hard to remove from observed point source samples.

We thank the referee J. Irwin, and also A. King and T. Maccarone for useful comments, and the Aspen Center for Physics and the NU Visitors' fund (to AZ) for support. We also thank M. Tosi and L. Angeretti for discussing their results prior to publication. This work is partially supported by a Packard Fellowship, and a *Chandra* theory grant to VK, NASA LTSA grant NAG5-13056 to AZ and VK and NASA grant NAS8-39073 to GF.

REFERENCES

- Aloisi et al. 2001, ApJ, 121, 1425
- Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289
- Beer, M.E. & Podsiadlowski, P. 2002, MNRAS, 331, 351
- Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407 (BKB)
- Belczynski, K., & Taam, R.E. 2003, ApJ, submitted
- Dubus, G. et al. 1999, MNRAS, 303, 139
- Fabbiano, G. & White, N. 2003, review
- Gehrels, N. 1986, ApJ, 303, 336
- Greggio, L., et al. 1998, ApJ, 504, 725
- Grimm, H.-J., Gilfanov, M., & Sunyaev, R. 2003, MNRAS, 339, 793
- Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
- Hut, P. 1981, A&A, 99, 126
- Israel, F. P. 1988, A&A, 194, 24
- Ivanova, N., Belczynski, K., Kalogera, V., Rasio, F., & Taam, R. E. 2003, ApJ, 592, 475
- Kalogera, V. & Webbink, R.F. 1996, ApJ, 458, 301
- Kilgard, R.E., et al. 2002, ApJ, 573, 138
- Kim et al. 2003, ApJ, in press (astro-ph/0308493)
- King, A.R. et al. 2001, ApJ, 552, L109
- Kroupa, P., Tout, C. A., & Gilmore, G. 1993, MNRAS, 262, 545

Levine, A., Rappaport, S.A., & Zojcheski, G. 2000, 541, L194
Martin, C. L., Kobulnicky, H. A., & Heckman, T. M. 2002, ApJ,
574, 663 (M02)
Mathieu, R. D., et al. 1992, "Binaries as Tracers of Stellar
Formation", ed. Duquennoy, A. & Mayor, M., Cambridge
University Press, p.278
Sarazin, C.L., et al. 2003, ApJ, 595, in press
Sipior, M., Eracleous, M., & Sigurdsson, S. 2003, ApJ, submitted
(astro-ph/0308077)

Taam, R.E., King, A.R., & Ritter H. 2000, ApJ, 541, 329
Vallenari, A. & Bomans, D.J. 1996, A&A, 313, 713
Van Bever, J., & Vanbeveren, D. 2000, A&A, 358, 462
Wu, K. 2001, Publications of the Astronomical Society of Australia,
18, 443
Zezas, A. & Fabbiano, G. 2002, ApJ, 577, 726